

15.0 The Visible Infrared Imaging Radiometer Suite (VIIRS)

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15.1 Introduction

The Visible Infrared Imaging Radiometer Suite (VIIRS) is used to obtain measurements of the Earth's oceans, land surface and atmosphere to make a wide range of Environmental Data Records (EDR's). These standard products, which have been defined in the Integrated Operational Requirements Documentⁱ (IORD), are listed in Table 15.1. VIIRS is designed to provide global coverage at least once per day, with moderate (better than 1 km) spatial resolution. This combination of spatial and temporal scales has been chosen to provide needed input to operational weather and environmental models while sampling the natural variability of biological processes on the land surface and in the oceans. It has very high radiometric and geometric fidelity, enabling its use in the acquisition of long-term data records suitable for the study of climate and climate change as well as being a powerful tool for studies designed to increase our understanding of specific geophysical processes such as the interaction of the biological and physical mechanisms in ocean plankton blooms.

VIIRS will fly on the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) in three polar sun-synchronous orbit planes with equator crossing times of 1730 (Ascending Node), 0930 (Descending Node) and 1330 (Ascending Node). It will also fly on the NPOESS Preparatory Project (NPP) with a 1030 Ascending Node. NPP will launch in late 2007; the NPOESS satellites are scheduled to be launched beginning about 2009.

Table 15.1. List of Data Products from VIIRS.

| Product Grouping | EDR/Other Product | Comments |
|-------------------------|--|---|
| Imagery | Imagery* | Manually interpreted |
| Surface Temperatures | Sea Surface Temperature* Land Surface Temperature Ice surface Temperature | |
| Clouds | Cloud Base Height Cloud Cover/Layers Cloud Particle Size Cloud Optical Thickness Cloud Top Height Cloud Top Pressure Cloud Top Temp. Cloud Mask | Supports CMIS Intermediate Product |
| Aerosols | Aerosol Optical Thickness Aerosol Particle Size | Separate alg. for land/ocean Separate alg. for land/ocean |
| Ocean Biosphere | Ocean Color/Chlorophyll | |
| Land Biosphere | Vegetation Index Vegetation/Type Albedo | |
| Snow & Sea Ice | Snow Cover Sea Ice age/motion | Supports CMIS Works w/ CMIS |
| Fire | Fire Detection | Not an EDR |
| Other | Soil Moisture Net Heat Flux Suspended Matter Geolocation | Supports CMIS Supports CMIS Intermediate Product |

* Key Performance Parameter

While the sensor is described as a “suite”, it consists of a single sensor; the original planning allowed for meeting the measurement requirements with either a single sensor or a small suite of sensors. VIIRS draws heavily on the experience gained in building and operating the Moderate Resolution Imaging Spectroradiometer (MODIS) that also combined diverse functions into a single sensor. It also draws on the experience with various sensors with specific tasks such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) for measuring ocean color, the Along Track Scanning Radiometer (ATSR) for measuring sea surface temperature, and the Operational Linescan System (OLS) for terminator imaging.

15.1.1 Spectral Band Compliment

VIIRS uses 4 Focal Plane Assemblies (FPA's) to hold the 21 spectral bands plus a “Day-Night Band” (DNB), a high sensitivity, large dynamic range, visible panchromatic band. The DNB and the 16 “M” bands have a moderate resolution of 740 m at nadir while the 5 “I” bands (for imagery) have a nadir resolution of 370 m. The visible and near infrared (VISNIR) FPA has 9 spectral bands with central wavelengths between 412 nm and 865 nm. The DNB FPA shares the same optical “focal plane” as the VISNIR FPA. The shortwave and midwave infrared (SWMWIR) FPA has 8 bands with central wavelengths between 1.24 μ and 4.05 μ . The long-wave infrared (LWIR) FPA has just four bands, with central wavelengths between 8.55 μ and 12 μ . Comparisons to predecessors are shown in Figure 15.1. The principle characteristics and these 22 spectral bands, including their principle uses, are shown in Table 15.2.

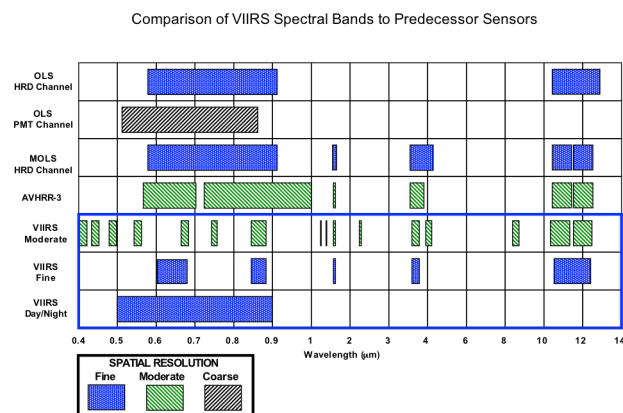


Fig. 15. 1. VIIRS and other imagers compared.

Table 15.2 VIIRS Spectral Bands and Their Principal Uses

| ID | Band Center nm/ μ | Band Width nm/ μ | Imagery | Surf Temp | Clouds | Aerosols | Ocean Color | Land Bio | Snow/Sea Ice | Fire | Other |
|------|--------------------------|-------------------------|---------|-----------|--------|----------|-------------|----------|--------------|------|-------|
| DNB | 700 | 400 | M | | M | | | | | | |
| M-1 | 412 | 20 | | | | M | M | M | M | | M |
| M-2 | 445 | 18 | M | | | M | M | M | M | | M |
| M-3 | 488 | 20 | | | | M | M | M | M | | M |
| M-4 | 555 | 20 | | | | M | M | M | M | | M |
| I-1 | 645 | 50 | I | | I | | | I | I | | |
| M-5 | 672 | 20 | | | M | M | M | | M | | M |
| M-6 | 751 | 15 | | | | | M | | | | M |
| M-7 | 865 | 39 | | | M | M | M | | M | | M |
| I-2 | 865 | 39 | I | | I | | I | I | I | | |
| M-8 | 1.24 | 0.02 | | | M | | | M | | M | |
| M-9 | 1.378 | 0.015 | M | | M | | M | | | | |
| M-10 | 1.61 | 0.06 | | | M | M | M | | M | M | |
| I-3 | 1.61 | 0.06 | I | | I | | | I | I | | |
| M-11 | 2.25 | 0.05 | M | | M | M | M | M | M | M | |
| M-12 | 3.7 | 0.18 | | M | M | M | | M | | | |
| I-4 | 3.74 | 0.38 | I | | I | | | | | I | |
| M-13 | 4.05 | 0.155 | M | M | M | | | | | M | |
| M-14 | 8.55 | 0.3 | M | | M | | | | | | |
| M-15 | 10.76 | 1 | M | M | M | | | M | | M | |
| I-5 | 11.45 | 1.9 | I | | I | | | | | I | |
| M-16 | 12.01 | 0.95 | M | M | M | | | M | | | |

* DNB = Day-Night Band

M=Moderate resolution Band (740 m)

I =Imaging Band (340 m)

15.2 Design Philosophy

Before describing the sensor design in detail, we begin with an overview of some of the factors that drove the design of VIIRS. These are also discussed in further detail in Ardanuy et al. (2001).ⁱⁱ

15.2.1 Spatial/Temporal Design Drivers

VIIRS is responsible for two Key Performance Parameters (KPP), the Sea Surface Temperature (SST) EDR's and the Imagery EDR. These EDR's are so critical that a replacement satellite will be launched if the VIIRS performance degrades in such way as to prevent their production at the required fidelity. The design of VIIRS was strongly driven by the particular requirements of these two EDR's and, to a lesser extent, by the other EDR's.

SST is a critical component of weather and climate models and a key indicator of long-term climate stability and climate change. It is derived from measurements in two spectral bands in the thermal IR region. Nighttime measurements of SST may utilize two additional bands in the mid-wave infrared. SST varies significantly from day to day and must be measured at least once in the daytime and once at night. The intrinsic spatial scale of variability for SST is on the order of a few kilometers, especially around the edges of ocean currents. This requires individual measurements to be at a slightly smaller scale, driving the spatial resolution to the sub-kilometer level even though the final standard data product will be reported at a horizontal cell size of 2.5 km. SST will be derived to an accuracy of better than 0.5° K.

The imagery EDR uses a large number of spectral bands in all spectral regions to produce images which can then be interpreted by skilled operators and/or automated computer algorithms to derive assessments of cloud cover and type, as well as ice edge location and concentration. Measurements are acquired in the daytime using both visible and infrared bands, while nighttime measurements rely entirely in the thermal infrared bands. The DNB provides near constant contrast imagery across the terminator and into the nighttime region at relatively coarse radiometric quality. It is capable of providing usable images under illumination by the quarter Moon. The DNB also provides a capability for the production of nighttime cloud masks, though there is no standard data product defined.

Some operational users of the VIIRS data have a need for nearly constant spatial resolution over the full field of regard. The distance from the spacecraft to a nadir location is 833 km, but to the edge of scan, five

degrees below the limb, it is over 1,800 km. As a result, the down-track length of a pixel doubles and, due to the curvature of the Earth, the cross-track length triples. VIIRS is designed to meet the spatial resolution requirements at the edge of scan, and aggregate pixels up to the required spatial resolution as the field of view approaches the nadir. As a result, no pixel is larger than 1.3 km within the central 1,700 km of the scan.

A set of EDR's address the measurement of land surface properties, including albedo, land cover, vegetation index, snow cover and land surface temperature. Biologically driven variations in the surface ecosystem depend on complex interactions among seasonal forcing functions, supply of nutrients, weather events that range from short- and long-term drought to the passage of frontal systems, and episodic events such as hurricanes or human-driven land cover change. Cloud free imagery of any region can usually be acquired within 5 to 10 days, just capturing such phenomena as the emergence of crops in the spring and the senescence of vegetation in the fall. Human-induced changes such as crop harvesting and deforestation, as well as some natural phenomena such as fires and floods can cause changes that are only partly sampled by the VIIRS sensor. Land data are needed at the scale of a few kilometers for some biospheric studies and at 10 to 20 km for radiation budget purposes. But the high spatial variability of the land surface and the non-linear nature of the algorithms dictate obtaining data at the sub-kilometer level, even down to a few hundred meters.

Ocean biological productivity is assessed through the measurement of ocean color. Seven spectral bands in the visible region are used for this purpose. The scale of ocean biospheric variability is well captured with 1 km measurements. Ocean plankton blooms have more rapid time scales than do land ecosystems, but the frequency of cloud cover makes it impractical to obtain the desired time resolution with optical sensors. The ocean biosphere has the additional complication that its ecosystems are moving and there is a complex interaction between ocean dynamics and biological processes. Further, the "sun glint" obliterates much of the needed data. A combination of two VIIRS sensors in different orbits with different viewing geometries reduces the impact of the sun glint and permits a good sampling of the natural variability.

The ocean and land surface properties are used for a wide range of operational purposes including fisheries, agricultural and land use assessments, as well as the scientific study of the global carbon cycle.

Another set of EDR's address the measurement of cloud and aerosol properties. The cloud EDR's rely primarily on infrared bands to measure cloud cover, cloud top temperature and pressure, effective particle size and

cloud base height. Reflected bands provide cloud optical properties during the day, and well as cirrus cloud detection. Aerosol properties include the aerosol optical thickness and particle size, as well as suspended matter (e.g. dust). Aerosol measurements rely primarily on visible and near infrared bands, along with the 2.25 μm band over the land. Both clouds and aerosols are critical components of the study of long-term climate change. These data are used for both operational (e.g. aircraft routing) and science (e.g. climatic studies) purposes. The timescale of natural variability, especially for clouds is quite rapid, and cannot be fully encompassed by a single VIIRS. By placing VIIRS on three satellites with different equator crossing times the diurnal variability is well sampled. This coverage is suited to weather models when coupled with data assimilation. Cloud and aerosol properties are needed at the 10 km level, but the spatial heterogeneity of clouds and the non-linearity of the cloud property algorithms again drive the scale of measurements to the sub-kilometer level.

Many of the measurements needed for the study of aerosols are also used for a critical intermediate product, the atmospheric correction. Land and ocean surface properties are determined from the surface reflectance or surface temperature, but VIIRS measures the reflectance or temperature of the combination of the surface and atmosphere. For example, more than 90 % of the reflectance measured in the critical ocean color bands comes from the atmosphere, and is, in effect, a bias that must be removed during the retrieval.

Additionally, a cloud mask is needed to determine whether or not a given pixel actually contains information about the surface. All algorithms work on the basis of spectral signatures, and the presence of even a small amount of bright cloud over the typically dark land or ocean surface can severely bias the algorithm's performance. (The same is generally not true for small amounts of surface reflectance in an otherwise cloud-covered pixel.) While clouds exhibit a continuum of spatial scales, the occasions where the sky is 90 % cloud free generally include only small amounts of fair weather cumulus. Driven by the height of the boundary level, they have characteristic scales of a few hundred meters. Thus it is necessary to have a few bands optimized for cloud detection and surface property determination at the highest spatial resolution possible.

VIIRS also measures a number of cryospheric properties, including snow cover, fresh water ice concentration, sea ice edge and edge motion, and ice surface temperature. A combination of visible and infrared bands is used to obtain these measurements. The cryosphere measurements are used

by operational users for navigation and for weather and climate modeling. The spatial requirements are similar to that of the land EDR's.

Finally, VIIRS works in conjunction with the Conical Microwave Imager/Scanner (CMIS) to provide measurements of net heat flux and soil moisture. The VIIRS role in these EDR's is supportive rather than primary.

15.2.2 Spectral/Radiometric Design Drivers

Land surface properties are primarily derived from the spectral information in the visible and near infrared region. The spectral features are diffuse and complex. The major difference amongst various soils is in their overall color and brightness. The spectral information in vegetation is overwhelmingly the signature of chlorophyll, which is measured with two well-placed spectral bands with moderately sharp bandpasses. The dynamic range has to allow for the typically low reflectances of vegetation and the higher reflectance of some bare soils and, of course, the very high reflectance of snow and ice. Since the same bands can be used for some cloud measurements, the dynamic range has to include even the brightest of clouds. The level of quantization (12 bits) is driven by the need to encompass this wide dynamic range while still providing adequate radiometric resolution for vegetated surfaces (reflectances are typically less than 3 %) near the terminator.

For ocean color the situation is more complex as there are a number of pigments besides chlorophyll that are measured. The spectral features are diffuse and overlapping, requiring well placed moderate bandwidth filters. Water is extremely dark, and as much as 90 % of the energy reaching the sensor comes from light scattered in the atmosphere. Ocean color sensors often allow the spectral bands to saturate over clouds and land in order to preserve the required radiometric resolution over ocean surfaces. In the case of VIIRS, it was decided to use the same spectral bands for both ocean and land to minimize data rate and to minimize sensor electronic and optical complexity. The bands that serve this dual purpose have dual gains, yielding the required radiometric resolution over the full dynamic range. These bands automatically switch from the high gain state to the low gain state when the radiance illuminating a detector exceeds a given value intermediate between the low and high ends of the full dynamic range. Dual gain switching occurs independently from detector to detector and sample to sample, so that the correct gain state is used regardless of the spatial or temporal variability of the scene radiance.

Many cloud and aerosol properties require information in the visible and short- to mid-wave infrared bands. The dynamic range required for land

and ocean is not quite sufficient for clouds, as clouds exhibit a strong backscatter, resulting in reflectances above 100 % of a diffuse reflectance. The spectral features used by the algorithms are again somewhat diffuse, requiring only moderate spectral resolution. A powerful way to obtain information on the presence of cirrus clouds requires a very well tailored spectral band at 1.38 microns. This band is deliberately placed in the midst of a strong water-vapor absorption region such that no radiance is sensed from a column unless high cloud is present to reflect the light before it is absorbed.

Table 15.3 Spectral and Radiometric Properties of VIIRS Spectral Bands

| Band ID | Band Center | Band Width | SNR/ NEDT | L_{typ} | L_{min} | L_{max} | SNR/ NEDT | L_{typ} | L_{min} | L_{max} |
|---------|-------------|------------|---------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| | | | Single or High Gain | | | | Low Gain | | | |
| M-1 | 412 nm | 20 | 352 | 44.9 | 30 | 135 | 316 | 155 | 135 | 615 |
| M-2 | 445 nm | 18 | 380 | 40 | 26 | 127 | 409 | 146 | 127 | 687 |
| M-3 | 488 nm | 20 | 416 | 32 | 22 | 107 | 414 | 123 | 107 | 702 |
| M-4 | 555 nm | 20 | 362 | 21 | 12 | 78 | 315 | 90 | 78 | 667 |
| I-1 | 640 nm | 80 | 119 | 22 | 5 | 718 | | | | 718 |
| M-5 | 672 nm | 20 | 242 | 10 | 8.6 | 59 | 360 | 68 | 59 | 651 |
| M-6 | 746 nm | 15 | 199 | 9.6 | 5.3 | 41 | | | | 41 |
| M-7 | 865 nm | 39 | 215 | 6.4 | 3.4 | 29 | 340 | 33.4 | 29 | 349 |
| I-2 | 865 nm | 39 | 150 | 25 | 10.3 | 349 | | | | 349 |
| M-8 | 1.24 μ | .020 | 74 | 5.4 | 3.5 | 164.9 | | | | 95 |
| M-9 | 1.378 μ | .015 | 83 | 6 | 0.6 | 77.1 | | | | 41 |
| M-10 | 1.61 μ | .06 | 342 | 7.3 | 1.2 | 71.2 | | | | 72.5 |
| I-3 | 1.61 μ | .06 | 6 | 7.3 | 10.3 | 72.5 | | | | 56.7 |
| M-11 | 2.25 μ | .05 | 167 | .12 | 0.12 | 31.8 | | | | 31.8 |
| M-12 | 3.70 μ | .18 | .396 K | 270 K | 230 K | 353 K | | | | |
| I-4 | 3.74 μ | .38 | 2.5 K | 270 K | 210 K | 353 K | | | | |
| M-13 | 4.05 μ | .16 | .107 K | 300 K | 230 K | 343 K | .423 K | 380 K | 343 K | 634 K |
| M-14 | 8.55 μ | 0.3 | .091 K | 270 K | 190 K | 336 K | | | | |
| M-15 | 10.8 μ | 1.0 | .070 K | 300 K | 190 K | 343 K | | | | |
| M-16 | 12.0 μ | 1.0 | .072 K | 300 K | 190 K | 340 K | | | | |
| I-5 | 11.5 μ | 1.9 | 1.5 K | 210 K | 190 K | 340 K | | | | |
| DNB | 700 nm | 400 | 6 | 6.7E-05 | 3.0E-05 | 2.0E+02 | | | | |

Data are from VIIRS Sensor Specification (Jan, 2002)

Other cloud properties make use of the thermal infrared region to measure cloud top temperatures. These same bands are used for determination of land, ice and sea surface temperatures. Inclusion of both

cloud top temperatures and surface temperatures places a strong demand on performance over a wide dynamic range, from 180 K to 340 K. Due to practical considerations, the calibration is best suited to the mid- to high-temperature end of the range.

The ensemble of these spatial, temporal, spectral and radiometric design constraints leads to the basic concept of the VIIRS sensor architecture, with some bands offering a nadir spatial resolution of 370 meters and others with 740 meters. Global daily coverage is obtained by having a large field of regard, scanning nearly from limb to limb. A scanning system rather than a step-staring system using large area arrays was chosen because of the large number of spectral bands required. With a large field of regard and with certain other sensor properties that have been chosen to meet the overall requirements, scattered light from bright areas into dark ones and from hot areas into cold ones becomes an issue. This scattered light issue then leads to the concept of using a well-baffled rotating telescope rather than a rotating scan mirror to gather the Earth scene and calibration data.

The spectral and radiometric properties of the 22 spectral bands are given in Table 15.3.

The basic building blocks of VIIRS are:

1. Rotating Telescope Assembly (RTA) that scans the Earth, on-board calibration targets, and deep space.
2. Half-angle Mirror (HAM) that de-rotates the image and directs photons into the aft optics.
3. Aft Optics Imager, consisting of:
 - A Four Mirror Anastigmatic (FMA) to image the target scenes onto the focal planes.
 - Two dichroic beam splitters to direct the photon stream onto 3 focal planes (one shared by the DNB and the Visible and Near IR FPA's).
4. Focal planes and associated support:
 - 2 ambient FPA's (the DNB and the Visible and Near IR FPA's);
 - A dewar;
 - 2 cooled FPA's (Mid-wave and Long-wave IR),
5. On-board calibrators consisting of:
 - A heated On-Board Blackbody Calibrator (OBC) for IR calibration;
 - A Solar Diffuser (SD);
 - A Solar Diffuser Stability Monitor (SDSM).
6. Cryoradiator;
7. Associated electronics consisting of:
 - Power Supplies;

- Signal processing electronics;
 - Data handling electronics.
8. Mechanical systems including an optical bench main frame and doors.

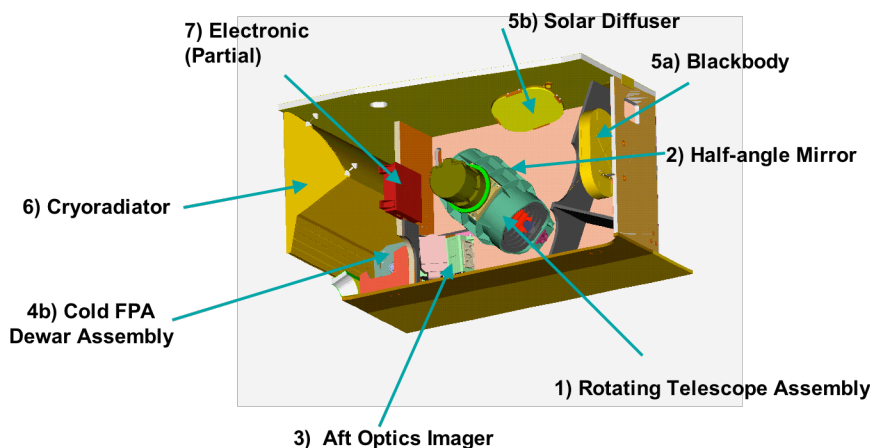


Fig. 15.2. Basic Building Blocks of VIIRS. (The Main Electronics Module (MEM) and the Solar Diffuser Stability Monitor (SDSM) are not shown.)

15.3 Follow the Photons

The key optical components are shown in Figure 15.3 to allow the reader to follow the path of photons as they enter the rotating telescope and pass through the various components. The sequence of views seen by the RTA is shown in Figure 15.4 and additional details of the components are shown in Figures 15.5-15.8.

15.3.1 Rotating Telescope Assembly (RTA)

VIIRS uses a rotating telescope to image the Earth nearly from limb to limb, deep space, and two calibration sources. The limits of the field of regard are at scan angles of $\pm 56.06^\circ$, which corresponds to a swath width of 3,040 km. This field of regard nearly covers the earth from limb to limb, since the horizon is at $\pm 62.19^\circ$. After scanning the Earth, the RTA scans the blackbody calibrator, which provides a high radiance reference for the thermal infrared bands, and then the solar diffuser, which provides a high radiance reference for the visible and near infrared bands. Finally, just before scanning back onto the Earth limb, it scans deep space to obtain a

low radiance reference for all bands. See Figure 15.4. About once per month the Moon will be visible through this “space view port”, allowing the use of the Moon as an alternate calibration source for the reflective bands. Each complete scan takes 1.7864 seconds; the Earth scan portion takes 0.55 seconds.

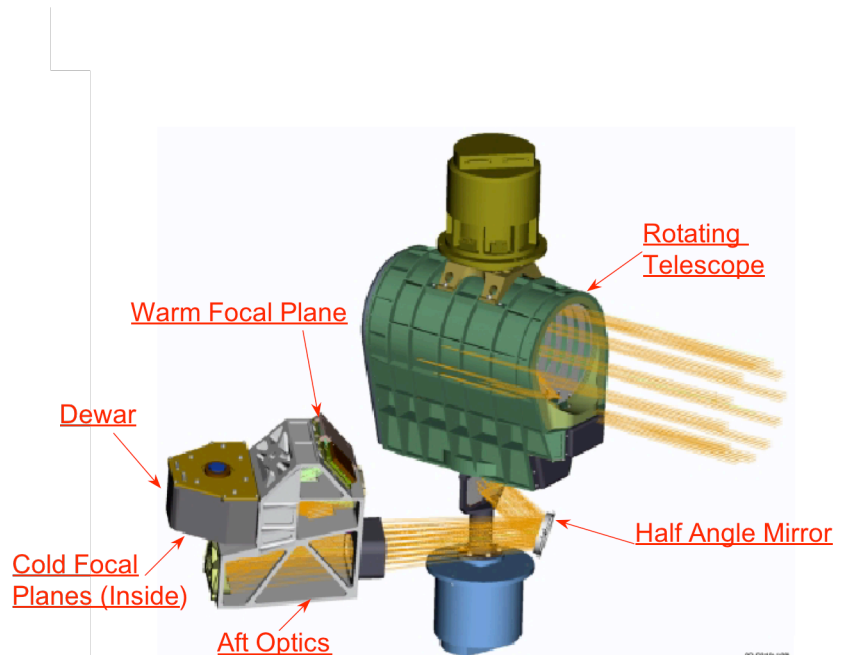


Fig. 15.3. The VIIRS Optical Path.

The RTA is an $f/6.2$ a-focal, off-axis Three-Mirror Anastigmat (TMA) with an effective aperture of approximately 8 inches. In addition to three powered elements, the RTA contains a fold mirror to constrain the overall dimensions. The primary mirror is a truncated circle (or D-shape) corresponding to the shape of the aperture stop, which is also a truncated circle designed to keep a clear path for the converging optical bundle while minimizing the Z dimension of the sensor. (The Z dimension of the sensor is the distance between the side of the sensor that mounts to the underside of the spacecraft and the side that faces nadir.) The RTA is extensively baffled and has an intermediate image plane (IIP) for additional baffling. Stay light is a concern for imaging across the terminator and over the dark ocean in the presence of both in-field and out-of-field bright clouds. The D-shaped aperture stop of the system is located between the HAM and the

Aft Optics in order to limit the field of view of the infrared detectors to the low-emissivity mirrors in the fore-optics. With this optical design the infrared detectors never view any of the warm, emissive structures in

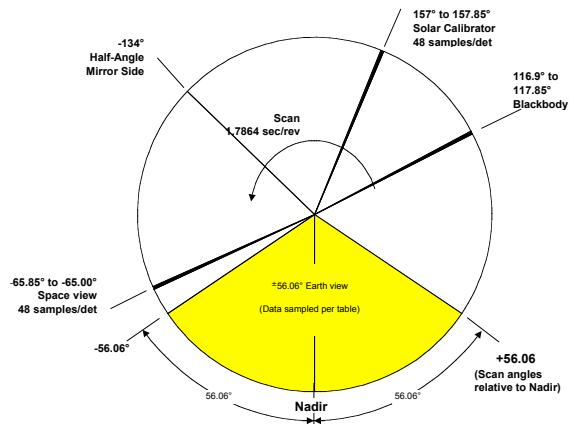


Fig. 15.4. Sequence of views obtained by the RTA.

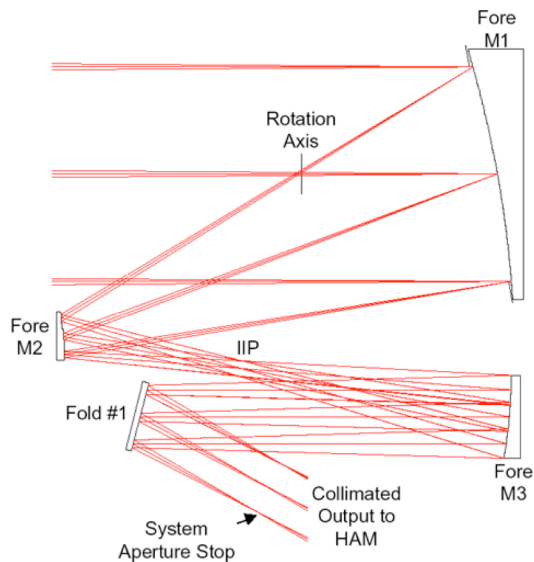


Fig. 15.5. The RTA features 3 powered mirrors and a fold mirror.

fore-optics at any point in the scan, thereby providing a stable infrared background due to internal instrument emission. The stability of the instrument background is essential to allow VIIRS to meet its stringent calibration requirements. Figure 15.5 shows the fore-optics and location of the system aperture stop. This and other optical schematics are simplified and do not show out-of-plane aspects of the ray traces.

15.3.2 Half Angle Mirror (HAM)

The half-angle mirror (HAM) rotates at half the speed of the RTA, effectively de-rotating the image and directing the photons to the fixed aft-optics. See Figure 15.6. Since it rotates at half the speed of the RTA, it is necessary to use one side of the mirror for one scan and the other for the next. The small differences in the optical properties of the two sides of the HAM must be accounted for in the Level 1 algorithm that produces calibrated radiances. Experience has shown that, even with extremely

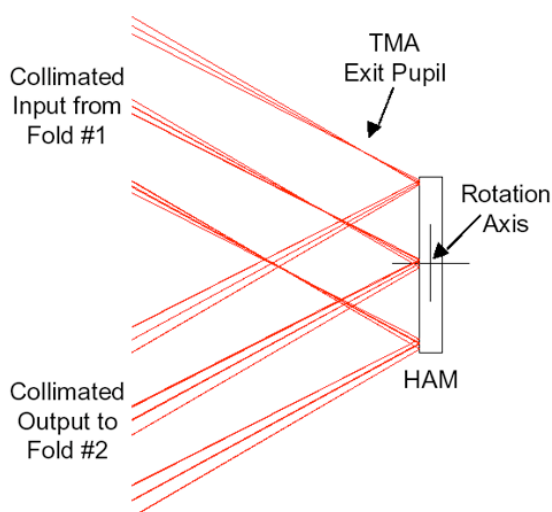


Fig. 15.6. The HAM receives collimated light from the fold mirror, which co-rotates with the RTA, and directs it to the fixed aft optics via another fold mirror.

careful control of the manufacturing and sensor characterization processes, there is still the possibility of some striping. The temperature of the HAM

must be known to within about $\pm 1\text{K}$ to calibrate the thermal infrared bands.

All mirror surfaces in the first flight model are aluminum with an overcoating of Denton FSS99-500 silver. Subsequent units may use an ion assisted deposition coating. The FSS99-500 coating has better polarization properties than do current ion assisted deposition coatings, but there are concerns over how it may deteriorate over the years of pre-launch storage that the later units must accommodate. Because of the wide range of angles of incidence at the HAM as the RTA scans the Earth and calibration targets, a low polarization sensitivity coating is required. The maximum polarization at a 45° scan angle is required to be less than 3% in the ocean color bands and is expected to be considerably less than that except for the 412 nm band.

15.3.3 Aft Optics

The aft optics imager is a Four Mirror Anastigmat (FMA) that images the incident scene on to the 4 FPA's. Like the TMA, it is an off-axis aspheric design. It has another intermediate image plane (IIP) for additional baffling of stray light. See Figure 15.7.

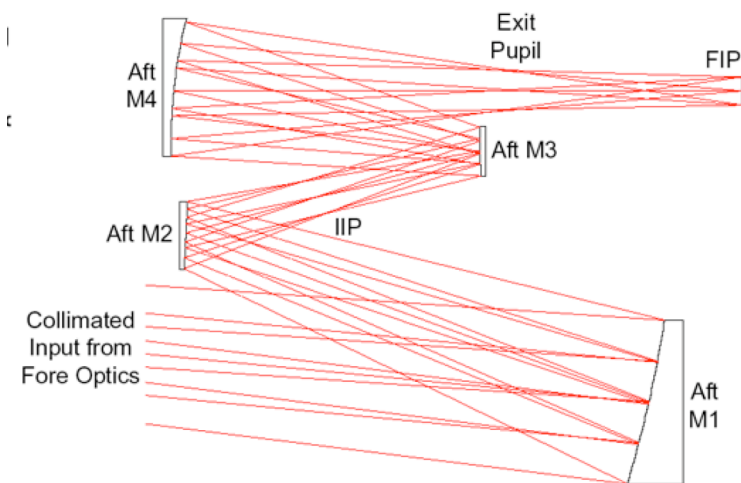


Fig. 15.7. Aft Optics Imager.

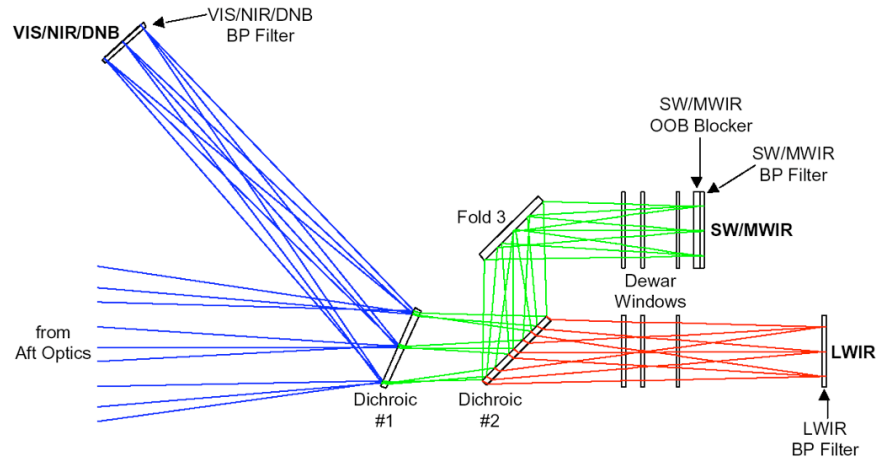


Fig. 15.8. Beam Splitters and focal plane assemblies

The remainder of the Aft Optics consists of two dichroic beam splitters, blocking filters and the focal plane arrays. See Figure 15.8. The converging beam from the Aft Optics Imager strikes a dichroic that reflects the VISNIR photons to the un-cooled FPA that contains the 9 VISNIR detector arrays and the slightly cooled FPA with the CCD for the Near Constant Contrast imagery over the terminator. Photons passing through the first dichroic strike a second dichroic that reflects the short and mid-wave infrared photons up to a fold mirror and then into a dewar containing the cooled focal plane operating at 80 K. Longer wavelength photons passing through the second dichroic and into the same dewar to the second focal plane operating at 80 K.

15.3.4 Focal Planes and Dewar

Each rotation of the VIIRS RTA sweeps out a path on the Earth that is just under 12 km down-track (at nadir) by 3000 km across track. For the M (Moderate Resolution) bands there are 16 detectors for each band while the I (Imaging Resolution) bands have 32 each. One band, M-16 at 12μ , uses two sets of detectors for Time Delay Integration (TDI) in order to achieve the required signal to noise ratio. All together VIIRS has 432 individual detectors plus the CCD array for the DNB.

The detectors are effectively rectangular in shape, with an instantaneous field of view (IFOV) of approximately 0.890 mr (740 m at nadir) down-track by 0.445 mr (318 m at nadir) across-track for the M bands. The I bands are approximately 0.445 mr (370 m) by 0.114 mr (95 m). At nadir three adjacent IFOV's are aggregated on-board to yield a single value corresponding to a square pixel (740 m for the M-bands and 370 m for the I-bands). As the scanner moves off-nadir the along-track geometric IFOV (GIFOV – the linear footprint in meters on the ground) grows due to the increased distance and, in scan (cross-track), due primarily to the view-angle, and to a lesser extent at the very edge of scan, also due to Earth curvature. At 530 km from nadir the electronics shifts to a two-pixel aggregation and restores the transmitted pixel to an approximate square. From about 850 to the edge of scan at 1,500 km there is no aggregation. See Figure 15.9. Only the single gain bands are aggregated on board in this manner. Dual gain bands are aggregated in ground processing, since the two gain states must be separately calibrated prior to aggregation. The CCD pixels are approximately 0.890 mr by 0.890 mr, corresponding to 740 m by 740 m at nadir.

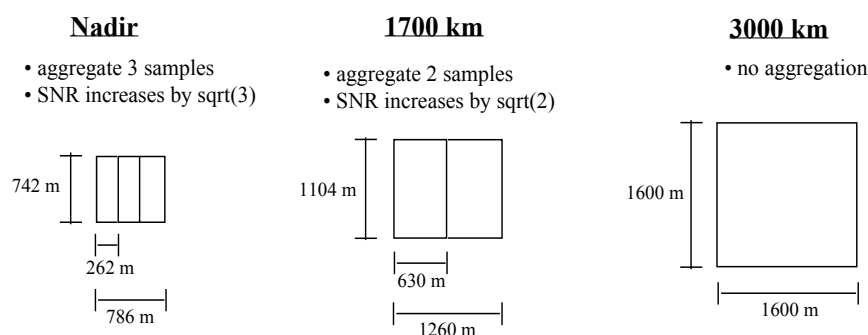


Fig. 15.9. Pixel aggregation scheme for the Moderate resolution bands.

The nine bands in the VISNIR FPA are silicon p-type intrinsic n-type (PIN) diode arrays. The SW/MWIR and LWIR bands are all photovoltaic Mercury Cadmium Telluride (HgCdTe) detectors. In order to reduce the size of the IR detectors and thereby reduce dark current and $1/f$ noise, the detectors have an integrated microlens array that converts the imaging bundle to approximately $f/1$. All detectors except the DNB CCD are hybridized to Read Out Integrated Circuits (ROIC) that contain their initial signal processing circuitry. Bandpass filters are mounted directly above the detectors or the microlens arrays for all but the DNB.

The DNB uses a monolithic CCD array. It has two identical high gain stages and on-board processing electronics to detect and correct for anomalous readings when detectors are struck by cosmic rays. The high gain stages use 250 detectors in TDI for each pixel, while the intermediate gain stage uses 3; the low gain stage has no TDI and uses a 45X neutral gain filter. The data are spatially aggregated on-board and transmitted with a gain-state bit.

The VISNIR FPA is uncooled and operates at an instrument ambient temperature of approximately 300 K. The DNB CCD is cooled by the cryoradiator and maintained at a temperature of $251\text{ K} \pm 2\text{ K}$ by a heater. This heater can also raise the temperature of the DNB to 300 K in order to repair damage due to space background radiation.

Six of the VISNIR bands are dual gain, allowing them to be used for dark ocean measurements or brighter land and cloud measurements depending on what is imaged. As stated above, these bands cannot be aggregated on-board, as the gain state is not known a priori.

Since all algorithms rely on the comparison of two or more spectral bands, it is essential that each spectral band view the same location. The general requirement for band-to-band registration is that they match 64 % of the area or better. For the most critical bands used for SST, the requirement is better than 80% of the area. Figure 15.10 shows the layout of the VISNIR FPA and the adjacent DNB FPA. The imaging bands are placed near the center of the focal plane to minimize optical distortions and to facilitate registration with imaging bands on the other two focal planes. M-3 and M-5 are also near the center because of the criticality of co-registration of these bands for some data products. Similarly, the 10.8 and 12.1 μ bands (M-15 and -16) used for SST are located near the center of the LWIR FPA.

Note that as VIIRS scans the Earth, a given location will be seen first by band M-1, then M-2, M-4, M-3, I-1, I-2, M-7, M-5, M-6 and the DNB. At the moment that M-1 detectors are imaging one area, M-6 is imaging an area about 6 km away. The SWMWIR focal plane is larger, spanning about 12 km in the scan direction.

The gain, noise and spectral bandpass characteristics of each detector will differ in small ways, and there will usually be a few detectors that have characteristics significantly “out of family” in their behavior. As a result, even when imaging a completely uniform surface, there will be some striping observed. Some, but not all, of this striping is removed by the calibration performed in ground processing for all bands. Residual striping in Imagery products can be further reduced by specialized destriping algorithms, but with a cost to radiometric accuracy.

The RTA rotates at a constant speed such that the spacecraft's down track motion equals the distance imaged by the 16 M-band detectors or the 32 I-band detectors at nadir during one scan period. On a given pass, detector 16 of an M band will provide a ground pixel followed by one from detector 15, and so on. At the beginning of next scan, the pixel adjacent to the one from detector 1 from the previous scan will be made by detector 16, but with the opposite side of the HAM in the optical train. This introduces a second level of striping, once per scan, in addition to the detector-to-detector striping.

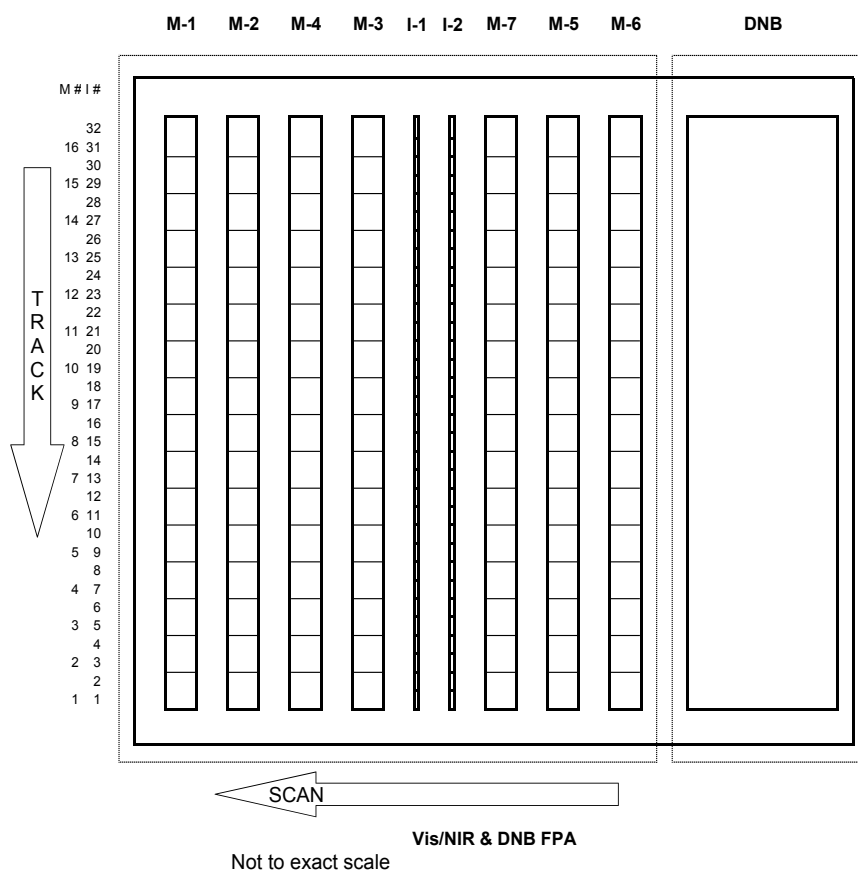


Fig. 15.10. VisNIR Focal Plane Layout.

The detector numbering system is natural for the flight software, but is inverted for image processing. While the operational software allows for this, those who choose to write their own software must keep this in mind.

The 16 detectors in the M-bands (and the 32 in the I-bands) match the down-track motion of the spacecraft at nadir, but off nadir the pixel sizes grow due to the increased range to the ground. At the edge of scan, the nominal 12 km down-track distance covered by the detector array has grown to nearly 24 km. This is known as the “bow-tie phenomenon” since the projected scan is shaped like a bow tie, narrow and the center and wider at the edges. This means that more than one detector will image a given spot on the Earth. While this redundant information is useful for reducing detector noise, about half of that data is trimmed from the data stream before it is transmitted to the ground in order to constrain the data rate. For the M-bands, data from detectors 1 and 16 are dropped at a scan angle of 31.59° . From 44.68° to the end of scan at 56.06° data is dropped from detectors 1,2,15 and 16.

15.3.5 On-Board Calibrators

VIIRS has very demanding requirements for radiometric accuracy. In general, the relative accuracy of the Level 1 radiances in the VISNIR region is to be $\pm 2\%$ for scenes of “typical radiance”. Calibration is accomplished by viewing a Solar Diffuser (SD). The SD is a full aperture calibrator that sits in the near field of the RTA. Its Space-grade SpectralonTM coated surface is carefully characterized in the laboratory prior to launch. Characterization includes both the absolute reflectance and the bi-directional reflectance distribution function (BRDF). A screen with a transmission of 11 % is permanently placed directly in front of the SD to reduce the intensity to levels that correspond to the expected intensity of Earth scenes. It consists of thousands of 0.75 mm holes on 2.0 mm centers. Signal to noise for the VISNIR bands during calibration are in excess of 1000:1 for all bands except I-3, which is approximately 500:1.

There is no door protecting the SD. The nadir doors and the use of a nitrogen purge during ground testing will limit contamination of the SD. In flight the solar diffuser screen will provide some protection for the SD.

Over time the reflectivity of the SD is expected to change, so there is a Solar Diffuser Stability Monitor (SDSM) to monitor the spectral reflectance in eight spectral bands between 0.4 and $0.86\ \mu$. The SDSM measures the ratio of the reflectance from the SD to that of a SpectralonTM coated integrating sphere that is directly illuminated by the Sun. Changes in the spectral reflectivity as small as 0.3 % can be tracked.

The SD and SDSM are measured once per orbit, near the South Pole as the satellite approaches the terminator. When VIIRS flies in the terminator orbit, the SDSM cannot be illuminated, so VIIRS calibration stability in

the VISNIR is monitored by cross-calibration with the mid-AM and mid-PM sensors. Moreover, the terminator VIIRS is less crucial for radiometric measurements than either the mid-AM or PM sensors.

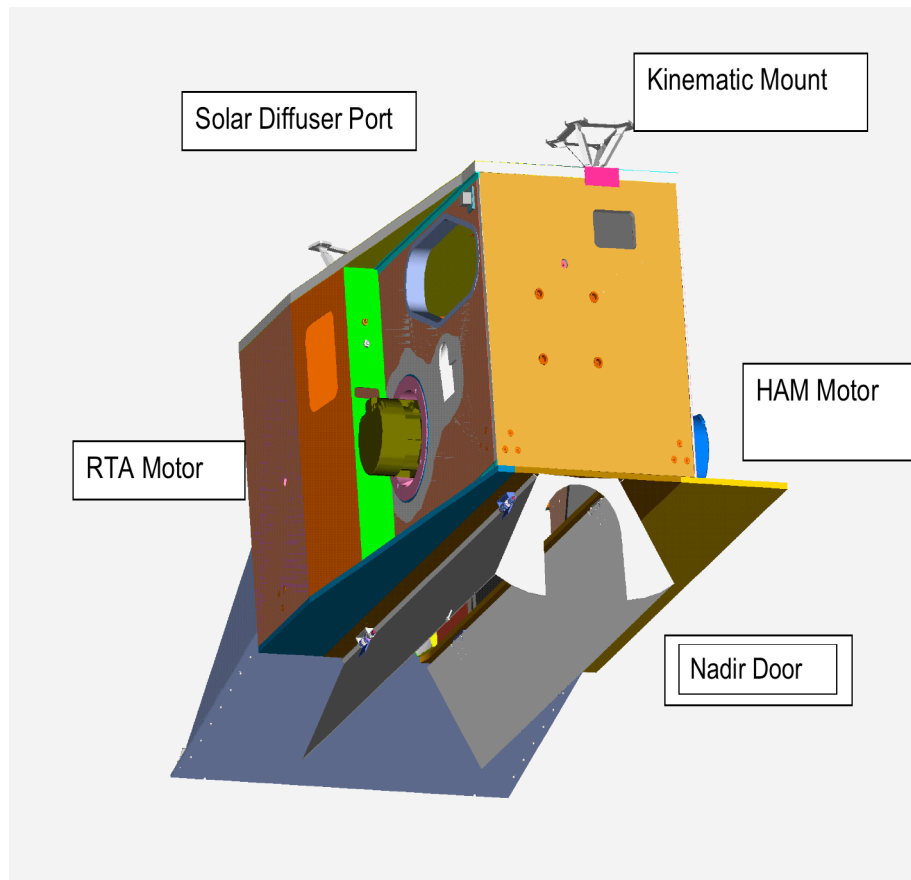
In the thermal infrared, the system is to meet an absolute accuracy requirement of 0.4 K in the LWIR. During each rotation the RTA scans a full aperture V-groove blackbody calibrator that is maintained at a constant temperature of $290\text{ K} \pm 0.200\text{ K}$. It can be heated up to 315 K to verify linearity of the IR detectors. The effective temperature of the blackbody can be determined from six embedded thermistors to within a calibration uncertainty of 0.05K over its operating temperature range of instrument ambient to 315 K. The blackbody temperature is traceable to NIST with an initial accuracy of $\pm 0.006\text{ K}$. The drift over a 17-year lifetime (including pre-launch storage and on-orbit operations) is predicted to be $\pm 0.011\text{ K}$. The V-groove design is similar to that used on MODIS. The internal groove surfaces have a specular black coating and geometry such that more than 90% of the light entering from the direction of the RTA undergoes 4 internal reflections before exiting the structure. The entire incident light from the direction of the RTA undergoes at least 3 internal reflections. The multiple internal reflections from the black surfaces ensure that the structure has a reflectance of less than 0.004 and therefore an emissivity greater than 0.996 in the direction in which the blackbody is viewed by the RTA. The blackbody is viewed on every rotation of the RTA. The average of 48 scans is used to provide the reference radiance for the IR bands. Like the SD, the on-board blackbody provides a full aperture calibrator.

There are no on-board calibrators for the DNB, which has relatively lax calibration requirements. Pre-launch calibration combined with cross comparisons to the VISNIR bands is sufficient. Signal offset data can be collected when it is viewing dark space and gain data can be determined for its least sensitive stage when it is viewing the solar diffuse

The Moon can be used as an additional calibration source. Approximately 7 times per year the Moon can be viewed directly by VIIRS during the deep space look at the end of the Earth scan. If the spacecraft were to be rolled less than 5° , the Moon could be viewed once per month, providing a completely stable external calibration source. Since the Moon's brightness varies strongly as a function of phase and libration angle, it is necessary to apply utilize an extensive database of ground-based observations and a model to obtain the reflectance at the time of the VIIRS observation.

15.4 Opto-Mechanical Systems

VIIRS consists of two modules that are independently mounted to the spacecraft, the VIIRS Opto-Mechanical Module (OMM), which contains the optics, focal planes, on-board calibrators and the cryoradiator, and the VIIRS Electronics Module (EM). The OMM is a trapezoidal solid that fits together with the electronics module within a rectangular envelope of 134 cm (X or velocity) by 141 cm (Y or anti-solar) by 85 cm (Z or nadir). The



total mass is less than 275 kg.

Fig. 15.11. VIIRS with doors deployed.

15.4.1 Structures

There are four structural bulkheads, made from honeycombed aluminum, that comprise the folded optical bench. The telescope and HAM bulkheads are rectangular plates on the +X (down-track) and -X (up-track) sides of the Opto-Mechanical Module. They are joined by the aft-optics bulkhead, forming a strong bent optical bench. A zenith bulkhead reinforces this strong bench, but has no optical elements attached to it. Additional panels, made from lighter weight honeycombed aluminum house the doors and baffles.

VIIRS is attached to the spacecraft by four kinematic mounts. (Four mounts are used rather than the typical three in order to reduce certain vibration modes during launch.

VIIRS has two deployable door assemblies, the nadir aperture door that consists of two separate panels, and the cryoradiator door. Both are one-time deployments. Figure 15.11 shows VIIRS once the doors have been deployed. When deployed, the nadir door acts as a baffle against extraneous light from the sun and the cryoradiator door acts to shade the radiator from heat load from the Earth.

15.4.2 Cryoradiator

The cryoradiator is a simple flat panel design with 3-stages. On orbit, the cold stage can reach a minimum temperature of less than 76 K, which allows the SWMWIR and LWIR detectors to be operated at a temperature of 80 K. The DNB is connected to the warm stage of the cooler. Once on orbit, the cryoradiator will be heated to a temperature of 270 K to drive off contamination from the spacecraft's hydrazine thrusters and residual vapors from entrapped water and other volatiles used in fabricating non-metallic parts of the sensor. This process can be repeated occasionally, if necessary, to maintain necessary cooler performance.

15.4.3 Thermal Control and Stray Light

Although VIIRS is planned for the three specific orbits specified in the introduction, it has been designed so that any build of the sensor can be flown in any of these orbits (or in other less favorable orbits) without modification to assure operational continuity. Passive thermal control of VIIRS is maintained with gold covered Kapton multi-layered insulation (or MLI) on the sunlit portions of VIIRS, which include the -Y side

(solar), +X side (ram), -X side (anti-ram), and -Z side (zenith). The +Z (nadir) side of the OMM is covered with a silvered Mylar and the +Z panel of the Electronics Module with white paint (YB71). The aft optics assembly, including the cold dewar, is thermally isolated from the main frame. Operational heaters are used to maintain the temperature of the scan motors above a minimum operating temperature of -5°C .

Stray light rejection is accomplished by numerous means. Given the wide range of illumination geometries encountered in the three nominal orbits over the course of a year, no single design can eliminate all scattered light. The VIIRS Sensor includes many design features to eliminate or significantly reduce its sensitivity to stray light including sources originating from direct solar or Earth illumination. The nadir aperture doors on VIIRS are angled to eliminate the scatter path from the Sun to the scan cavity for all orbits. The RTA includes an integral baffle coated with a very low reflectance black paint that rejects scattered light using geometric blockages. The optical system includes two intermediate image planes, one in the RTA and one in the FMA, where aperture stops can be employed to limit the transmission of off-axis stray light. Finally, the mirror surfaces are polished to provide better than a 25-angstrom surface roughness such that all illumination except direct sunlight on the primary will result in acceptable levels of scatter within the Sensor. However, even with all of these design considerations taken into account, there will still be brief times near the vernal equinox when sunlight can impinge directly on the primary mirror as the satellite passes near the South Pole. This effect, which is expected to amount to less than 0.5% of the operational time, is observed only in the terminator orbit.

The all-reflecting optical system uses diamond turned optics with nickel coatings. This relatively low cost optics is then polished to achieve the required surface to within 25 angstroms. The fore-optics assembly is made of aluminum. The aft-optics are made from aluminum, titanium, tungsten, and, in the dewar, beryllium.

15.5 Electronics

Most of VIIRS electronics are contained in the Electronics Module that is independently mounted to the spacecraft adjacent to the Opto-Mechanical Module. The Electronics Module includes the power supplies, the signal processing electronics (including the analog signal processors (ASP) and the digital pre-processors), the single board computer (SBC) and IEEE 1394 interface electronics), the Command and Telemetry electronics, and

the scan servo controllers and mechanisms chain. The system is fully redundant with options to cross-strap between the primary and redundant electronics in blocks (power supply A or B, signal processing chain A or B, and servo mechanisms A or B). Extensive use is made of Field Programmable Gate Arrays (FPGA) throughout.

15.5.1 Signal Processing and Transmission

The flow through the electronics module is shown in Figure 15.12.

The Analog Signal Processor (ASP) receives the analog output of the detectors and applies corrections for gain and offset for each of the 432 individual detectors and then converts the analog signal to a 12 bit digital signal. The ASP can adjust the detector offsets in real time to keep the analog signals from the detectors within the desired input range of the Analog-to-Digital Converter (ADC). This is done using an on-board look-up table that provides offset data to the ASP for each detector based on the response of the detector when viewing the on-board blackbody. This function, called “DC restore”, ensures that the digital output for all detectors is approximately 200 counts during the deep space view. The gains for each FPA are set by selection of resistors. The gain is chosen to maximize the use of the ADC input range, while providing adequate margin to avoid saturation for detectors that are more responsive than the average detector in an FPA.

For the DNB, there is a separate unit, the Focal Plane Interface Electronics (FPIE) that resides in the main Opto-Mechanical Module and performs the functions of the analog signal processor and then digitizes the signals prior to transmitting directly to the digital pre-processor in the Electronics Module. The FPIE also conditions the clock and bias signals that are applied to the DNB FPA and passes the power from the Electronics Module to the DNB. Additional circuitry in the Electronics Module compares the corresponding signals from the two independent high gain stages to detect erroneous signals due to cosmic ray hits and then either averages the output of the two stages if no anomalies are detected or transmits only the lowest amplitude signal from either stage if a significant difference is detected. Finally, the appropriate gain stage is selected and coded into the output digital signal that then contains 15 bits. These 15 bits consist of either 12 or 13 bits of detector data plus one or two bits that indicate the stage that the data is from.

The digital pre-processor performs the in-scan aggregation, combining 3 raw pixels into one transmitted pixel at nadir, two into one at 530 km from nadir. No aggregation is performed from 850 km to the edge of scan. The

six bands with dual gains are transmitted without aggregation. Science data is then compressed using a spectral differencing method (where the signals from the detectors in one band are subtracted from the signals from detectors sensing the same point on the Earth in one or more other bands) followed by a lossless compression method based on the USES implementation of the Rice algorithm developed by NASA's Goddard Space Flight Center (GSFC).

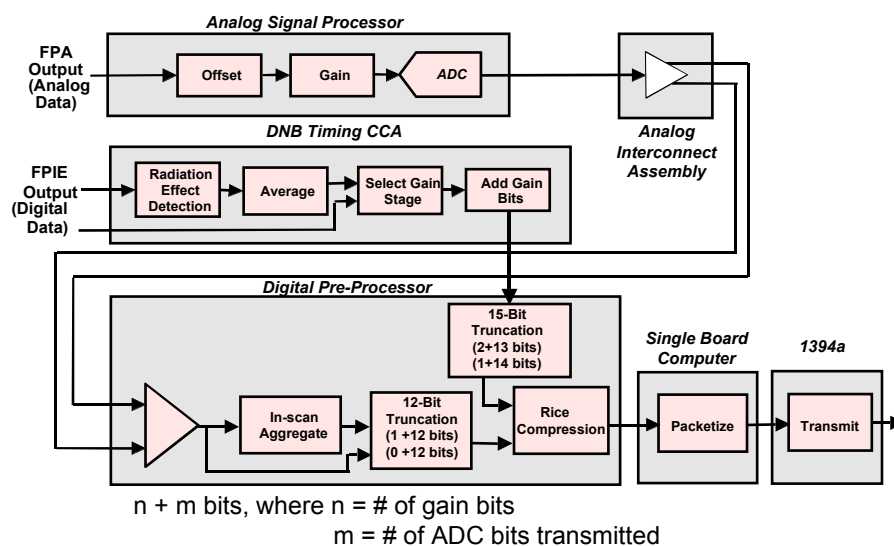


Fig. 15.12. Data Flow.

All data is output on an IEEE 1394 (Firewire) data bus. VIIRS and several other NPOESS sensors will be the first space-borne sensors to use this high-speed data protocol. The development of space-qualified chips to execute this popular protocol was in itself a significant achievement.

Within the digital pre-processor there are a number of programmable adjustments to the timing that are needed to assure proper geolocation and band-to-band registration. In effect, the adjustments change the time that a given set of detectors is read out, effectively shifting the Earth location of the pixels. Two adjustments are available to correct for misalignment between the encoders and the actual pointing of the RTA and the HAM. Other programmable adjustments allow the three focal planes to be brought into alignment, fine tuning the basic mechanical alignment. Since

they are accomplished through timing adjustments, these corrections are available only in the scan direction.

The Single Board Computer (SBC) is a radiation-hardened version of the 100 MIPS Motorola 603e microprocessor at its core. It carries 64 MB of RAM and 4 MB of EEPROM. Its functions include overall control of the VIIRS Sensor, collection of Sensor telemetry, execution of commands that have just been received from the spacecraft/ground control or that were previously stored in a time-tagged command table, and packaging and routing compressed Science data from the digital pre-processor to the EEE 1394 electronics.

Some of the key sensor parameters that are transmitted to Earth include the bias voltages applied to the detectors, the readings from the 6 thermistors on the blackbody calibrator, the temperatures of the blackbody calibrator, the HAM and various Sensor panels and subassemblies, and the cold FPA, and the rate data from the scan controllers. Note that the RTA temperature is not directly measured, but is inferred from a pair of nearby thermistors on the blackbody shield. The HAM temperature is also not directly measured, but is inferred from a thermistor inserted within the shaft that rotates the HAM, and is radiatively coupled to the rotating shaft. The HAM and RTA temperatures are indirectly measured because of the difficulty of instrumenting moving parts with thermistors in a system that must have very high reliability over a long mission life (seven years).

15.5.2 Power Supplies and Control Systems

Separate power supply modules power the digital, analog, and motor electronics and operational heaters, and outgas heaters. A total of 9 different voltages are required. The power supplies for the digital and analog electronics must be very well conditioned. When in normal operation mode the Sensor is expected to dissipate approximately 170 Watts, however, up to 200 Watts is required when the on-board blackbody is being heated to 315 K. The Sensor requires approximately 320 Watts of power when the outgas heaters are being operated.

Cold focal plane temperatures can be controlled to three set points: 76 K, 78 K, and 80 K. Accuracy is ± 0.05 K. Current plans are to operate the system at the highest temperature as this simplifies the pre-launch calibration and predicted performance if the detectors at 80 K meet all requirements.

15.5.3 Operational Modes

VIIRS is designed to operate autonomously for up to 60 days, though more frequent command uploads are planned. Its primary modes of operation are given in Table 15.4 together with some of the key properties of each mode. Once operations have begun, VIIRS is expected to remain almost exclusively in the Operational Day or Operational Night. In the Operational Day mode, data are collected from all bands. In the Operational Night mode, only the data from the DNB and bands I-4, I-5, M7, M8, M.10, and M-12 through M-16 are transmitted. The Operational Day mode is used whenever any portion of a scan line views the Earth with solar illumination at a solar zenith angle of 95° or less. In the Diagnostic mode, un-aggregated data can be transmitted.

Table 4: VIIRS Operational Mode Characteristics

| | RTA Power | Telescope View | Science Data | Houskeeping Data | Compression | Doors |
|-------------------|--------------|-------------------|-----------------|---------------------|--------------|--------|
| Operational Day | On | Earth/Cal | Yes | Yes | On | Open |
| Operational Night | On | Earth/Cal | Yes* | Yes | On | Open |
| Diagnostic | Var | Var | Var | Yes | On or Bypass | Open |
| Outgassing | Off | Anti-Nadir | No | Yes | N/A | Open # |
| Safe Hold | Off | Anti-Nadir | No | Yes | N/A | Open |
| Survival | Off | N/A | No | No | N/A | Var |
| Activation | Off | N/A | No | Yes | N/A | Open |

* Bands I4, I-5, and M-12 through M-16 only

Initial outgassing will have nadir door closed

Acknowledgements

The authors were all involved in the evolutionary design of the VIIRS instrument, either as the primary developers within the Raytheon organization or as part of the government team that represented the user community interests.

The authors wish to acknowledge the contributions of many individuals who made major creative input to the basic design of the VIIRS sensor. Within the Raytheon team, Rod Durham has served as the Program Manager since the project's inception. The late Gerry Godden as well as Richard Julian and Jim Young played critical roles in many aspects of the

design of VIIRS. Pete Kealy and Shawn Miller played equally critical roles in the development of the VIIRS algorithms and the tradeoff between sensor design and algorithms. Early in the program Marty Greenfield and John Pollicastro led a study to accommodate additional NASA requirements, which in turn led to the joint IPO-NASA NPP mission.

Others from the Raytheon team who played major roles in the design and development of VIIRS include Robert Aguilera, Vernon Alfred, Ron Estes, Craig Kent, Jay Neuman, Cliff Nichols, Dan Pelham, Don Pies, Joe Walker, Mike Whalen, and Jeanette Woo.

From the government team, members of the IPO staff, members of the VIIRS Operational Algorithm Team (VOAT) and other technical advisors have contributed to the design of VIIRS. Mike Crison who was the first IPO Instrument Manager and later the Payloads Manager played an essential role in defining the nature of the VIIRS sensor as did Carol Welsch. Major contributions were made by technical advisors Neal Baker and Hilmer Swenson. Other contributors were Bill Barnes, Wayne Esaias, David Glackin, Bruce Guenther, Mike Haas, Alex Lyapustin, Paul Menzel, Peter Minnette, Jeff Privette, Tanya Scalione, Art Schwalb, and Ken Speidel.

From the Northrop Grumman team, which serves as the Shared System Performance Responsibility contractor to the government, Technical Director Lane Darnton has played a major role during the detailed design and implementation phase. Other key contributors include Ed Hess, Jim Klein, and Steve Mills.

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